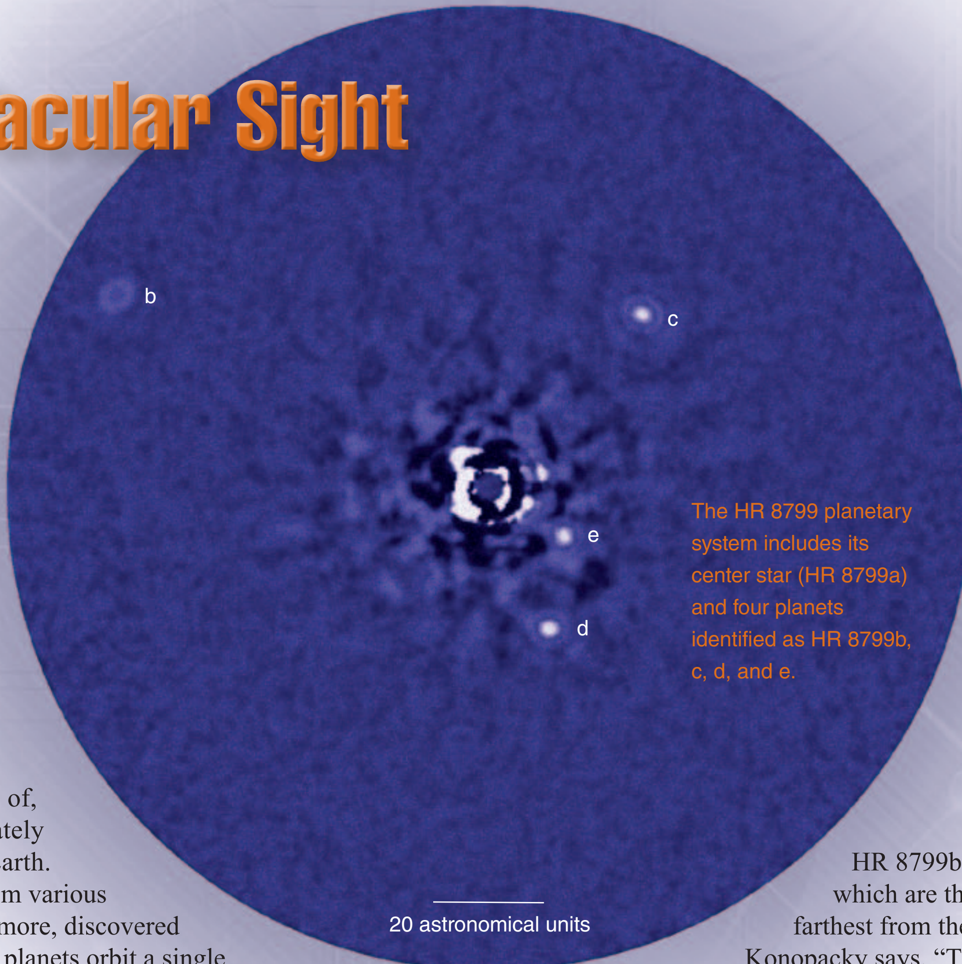
A Spectra-Tacular Sight



The HR 8799 planetary system includes its center star (HR 8799a) and four planets identified as HR 8799b, c, d, and e.

IN space and among the stars, astronomers and astrophysicists look for answers to the most fundamental questions regarding our existence. Earth lies in a planetary sweet spot, known as the Goldilocks Zone, where conditions are not too cold and not too hot, but just right for life to thrive. For a little more than a decade, scientists have been actively searching the vast expanse of space for solar systems with planets—called exoplanets—that are possibly similar to our own. These "sister" systems may in turn provide insight into what exoplanets are made of, how they form and evolve, and ultimately whether life exists in places besides Earth.

In a landmark study, researchers from various institutions, including Lawrence Livermore, discovered a distant solar system in which several planets orbit a single star known as HR 8799, a formation similar to Earth's solar system. Livermore astrophysicist Bruce Macintosh says, "We looked at approximately 400 stars during our search for exoplanets, and what we found here is extremely rare." Interestingly, the four planets within the system are three to seven times the mass of Jupiter and orbit at a distance of 15 to 70 astronomical units (AU) from HR 8799—where 1 AU is the distance from Earth to the Sun, or nearly 150 million kilometers. "It's a mystery how planets that big form so far away from their parent star," says Macintosh. These giant planets orbiting on the outside of the system could indicate that smaller, Earth-like planets exist closer to the star.

This year, Macintosh and former Livermore postdoctoral researcher Quinn Konopacky worked in collaboration with scientists from the National Research Council Canada's Herzberg Institute of Astrophysics and Lowell Observatory in Arizona to characterize the planets in the HR 8799 system. Using the OSIRIS integral field spectrograph and a high-powered telescope at Keck Observatory on the island of Hawaii, Macintosh and colleagues measured the spectra emitted to determine the plantets' atmospheric makeup. In particular, they analyzed planets HR 8799b and c, which are the two farthest from the star. Konopacky says, "This research represents the first time that molecular features have been seen at such a detailed level within exoplanets." The team's work was funded by Livermore's Laboratory Directed Research and Development Program.

Without a Doubt

Direct spectroscopy of exoplanets is extremely challenging for several reasons. "Because light from the star is so much brighter than light from the planets, we have to find ways to remove the starlight to extract the planet signal," says Konopacky, now a postdoctoral fellow at the University of Toronto. The problem is further compounded by Earth's atmosphere, which scatters light, making objects even harder to differentiate.

OSIRIS and the 10-meter Keck telescope proved to be ideal tools for overcoming these barriers. OSIRIS works in conjunction with the telescope's precise adaptive optics system to sample a rectangular area of the sky, separately recording the individual spectra of objects within its field of view at high resolution. One benefit of OSIRIS is that researchers can take such spectrographic measurements without having to line up the instrument directly with the object they are analyzing. The team also developed advanced image-processing algorithms and filtering techniques to more accurately distinguish the planet from the scattered starlight.

Different molecules absorb light at different wavelengths; thus, the light emitted from a planet directly correlates to the molecules in its atmosphere. “Molecular features have a specific spectral fingerprint that indicates the presence of a molecule without ambiguity,” says Macintosh. However, scattered starlight mimics the signals of interest and manifests itself as “speckles” in the images, effectively masking the planetary spectra.

To solve this problem, Macintosh developed an algorithm to help suppress and remove the scattered starlight. Spectrographic data are represented in “cubes,” where the *x* and *y* axes show the image of the field, and the *z* axis consists of slices of light at different wavelengths. Over time, the star’s and planet’s positions remain fixed within the cube, while the speckles appear farther from the center of the star at longer wavelengths. (See the figure below.) “We take advantage of how the positions of the speckles change with wavelength to more easily remove them from the data,” says Macintosh. The code accounts for the speckles’ brightness and changing position through the cube. It then subtracts them out, while maintaining the integrity of the planet’s signal. Macintosh adds, “The problem with previous algorithms is that they remove 90 percent or more of the speckle light, and with it, 20 percent of the light from the planet in a biased way.” This new linear algorithm is powerful because of its simplicity. It removes about 50 percent of the noise but does not inject any bias into the measurement of the planet.

Data were collected over 2010 and 2011 at the full spectral resolution provided by OSIRIS and input into computational models for analysis. Armed with the new filtering techniques, the team reduced and analyzed all the spectra and discovered the HR 8799 planets have high concentrations of water and carbon monoxide, uncharacteristic of giant gas planets in our solar system.

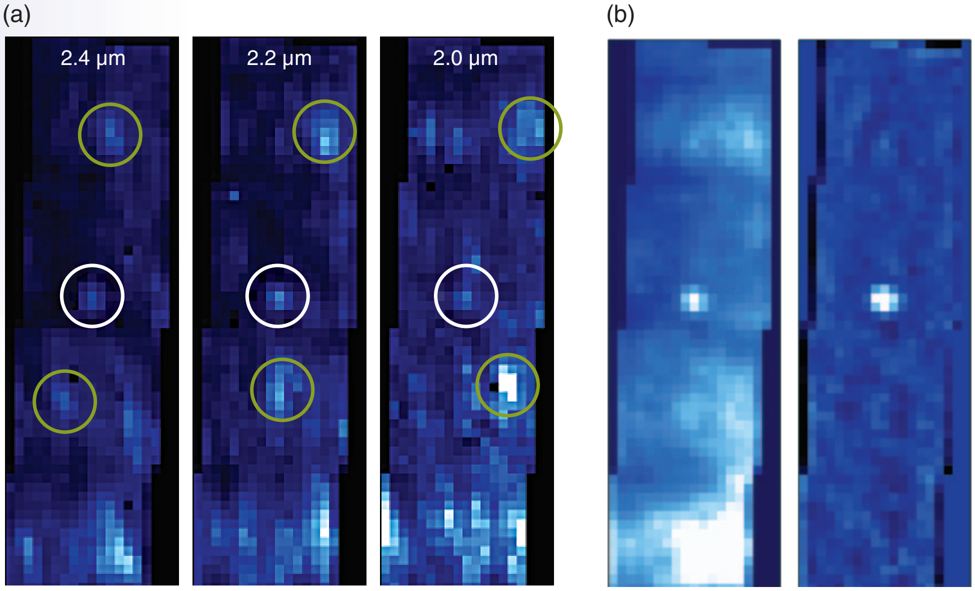
Surprise, Surprise

One theory for how planets form, including giant gas planets such as Jupiter and possibly those in the HR 8799 system, is through core accretion. In this process, a cloud of interstellar gas, comprising mostly hydrogen, forms into a star and a protoplanetary disk. Cooler regions on the outskirts of the disk contain icy planetesimals, made from molecules including frozen water and carbon monoxide, which stick together to create a planet’s core. When the core’s mass is big enough, it sucks excess gas from the cloud around it to form a giant gas planet that contains more of the materials in the form of solid ices (including oxygen, carbon, and nitrogen). In contrast, planets such as Earth are too small, and formed too late, to pull in gases from the surrounding cloud and thus have a wholly different chemical composition.

As a result of this formation process, giant gas planets primarily comprise hydrogen with a smattering of heavier elements such as carbon. As the planets cool, most of the carbon forms into methane. Surprisingly, the planets in the HR 8799 planetary system have more carbon monoxide than methane. Other, more refractory elements form dust clouds. Of interest is that the HR 8799 planets have much thicker dust clouds than predicted by older models.

“Results like this tell us that something unusual is happening,” says Macintosh. “Conditions within the planets are causing their atmospheres to circulate, pushing the methane down and the carbon monoxide and clouds up.” The large amounts of carbon

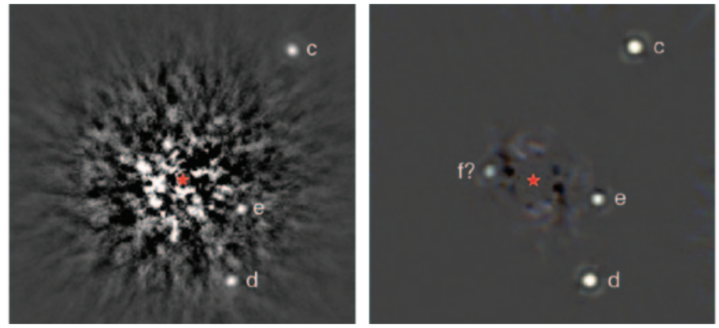
(a) (b)



(a) Three wavelength “slices” of data are taken from the OSIRIS integral field spectrograph at near-infrared wavelengths ranging between 2.0 and 2.4 micrometers (μm). The *x* and *y* axes represent position, and the star is to the right (not pictured). The speckle artifacts (yellow circles) are further from the star at longer wavelengths, while the planet (white circle) stays fixed, thereby allowing researchers to remove the speckle noise and enhance the planet. (b) These two images show a combination of about 200 wavelength slices between 2.0 and 2.4 μm before (left) and after (right) the speckle artifacts are removed. (Courtesy of Quinn Konopacky, University of Toronto.)

monoxide suggest that more carbon and oxygen were available when the planets formed. Macintosh says, "Excess oxygen and carbon in the HR 8799 planets means they probably formed through core accretion, which is a process that can theoretically also make Earths."

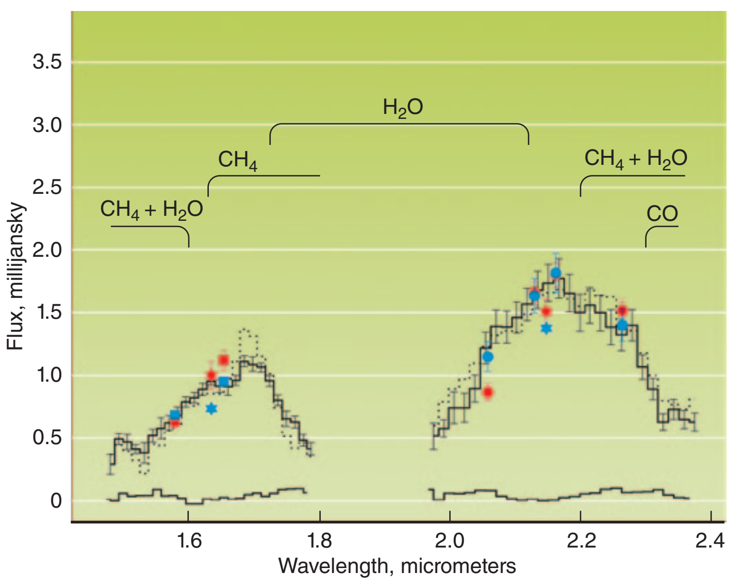
Konopacky is continuing to study the atmospheric phenomena in more detail. "We're using spectrographic measurements to determine the metallicities and ratio of carbon to oxygen within the planets," he says. Recent analysis of the data indicates that planet HR 8799c is hotter than HR 8799b and contains even more carbon monoxide. "We're still in the process of determining exactly what the molecular features are telling us about the planets and the potential implications of those findings," says Konopacky. "We may be heading into really exciting territory."



Side-by-side images of HR 8799 compare the image contrast achieved with the Keck telescope (left) to simulated results from the Gemini Planet Imager (GPI) in Chile (right). With GPI, a hypothetical exoplanet labeled "f" is clearly visible. (Courtesy of Christian Marois, National Research Council Canada.)

Are We Alone?

The holy grail of exoplanet research would be to find a small, rocky planet with a similar chemical composition to Earth orbiting a star. However, Earth-size planets are 10,000 times fainter than their giant planet counterparts and much too small to view with current technology. More advanced, precision instruments will be required to observe these planets at high enough resolutions that they can be studied in detail.



This plot shows the near-infrared spectrum of planet HR 8799b as captured by the OSIRIS spectrograph and Keck telescope in Hawaii. HR 8799 planets have high concentrations of water (H_2O) and carbon monoxide (CO). (CH_4 is methane.) The solid line with error bars shows the measured spectrum, while the dotted line indicates the spectrum before the speckle noise is removed. The solid lines at the bottom depict errors in measurements of simulated test planets with known spectra, which enable researchers to check for biases in the analyzed data. Colored symbols show measurements made with the Keck telescope's NIRC2 camera. (Courtesy of Travis Barman, Lowell Observatory.)

Toward this end, Macintosh is spearheading an international effort to install the Gemini Planet Imager (GPI, pronounced gee-pie) at the Gemini South telescope in Chile. (See *S&TR,* March/April 2008, pp. 4–10.) The sensitivity of GPI is much higher than any other instrument for directly observing distant objects. With GPI's sophisticated and improved adaptive optics system, astronomers will be able to detect objects more than 10 million times fainter than their parent stars. The system also includes a spectrograph for measuring atmospheric data. The spectrograph is an improved version of OSIRIS, and a team at the University of California at Los Angeles is tuning it specifically for hunting planets. "GPI will allow us to make many hundreds of observations for building our understanding of how planets form and evolve," says Macintosh. Looking up through Earth's atmosphere on an 8-meter telescope, GPI will still not be sensitive enough to see an Earth-like planet, but it should enable researchers to discover dozens of previously hidden giant planets.

With improved planet-detecting capabilities, will sleuthing astronomers find that Earth is one among many of its kind or the exception to every rule? Only time will tell whether the search for other Earths will lead to the discovery of life on other planets.

—*Caryn Meissner*

Key Words: core accretion, exoplanet, giant gas planet, HR 8799, Keck telescope, OSIRIS integral field spectrograph.

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